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Revisiting Deep Geothermal Power in the United Kingdom

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ABSTRACT

It is predicted that geothermal power will play an increasing role in renewable electricity generation (MIT, 2006). In addition, a growing proportion of geothermal power is expected to be derived from deep, low permeability rocks. Trials of deep geothermal systems in low permeability rocks first started in the mid 1970s, in the United States, the United Kingdom and Japan. The United Kingdom research project ran for the best part of 15 years and contributed substantially to the technical knowledge of rock mechanics and reservoir development.

This paper summarises the geothermal resource in the United Kingdom, the previous research project and the proposed deployment of a 10MW pilot power plant. The data from the original research project and other studies has been re-examined and a potential site selected. In addition, the lessons learnt from the original program will be applied to both the drilling and reservoir development program. Drilling of the exploration borehole is expected to start in 2010.

1. INTRODUCTION

As in many countries, the rapid increase in the oil price during the 1970s led the United Kingdom to investigate alternative energy resources, including deep geothermal. In the mid 1970s the British Geological Survey (BGS) was commissioned to assess the geothermal potential of the United Kingdom. Despite its location on the stable fore-land of Europe, remote from active volcanism and strong tectonism, surface heat flows and geothermal gradients indicated that economically useful temperatures of 60–100°C would be reached at depths of 2 to 3.5 km (Dunham 1974).

The research that followed included the production of a geothermal map of the UK published at a scale of 1:1 500 000 (Downing & Gray 1986) and ten-year deep aquifer research programme, published by ETSU (1986). A calculation was also made of the expected temperatures at significant depth (7kms) and this is shown in Figure 1. Although the calculated temperatures could be regarded as relatively low compared to some of the hottest geothermal resources in the World, it can be seen that, particularly in far South West of the United Kingdom, the potential does exist for deep geothermal power generation. These prospects warranted further research and the Camborne School of Mines started an extensive research into the rock mechanics of deep geothermal reservoir creation. This programme was undertaken at a site in the Rosemanowes Quarry in Cornwall (Figure 2) and explored the possibilities of developing the Carnmenellis Granite as a geothermal reservoir.

2. SUMMARY OF PREVIOUS RESEARCH

The research project on the Carnmenellis granite started in 1977. From 1980, the project was funded mainly by the UK Department of Energy. The objectives of the project were to investigate the engineering requirements for developing deep geothermal reservoirs, and to establish the size and nature of the deep geothermal resource in southwest England (Parker 1989). It was one of the largest hydrogeological experiments carried out in the United Kingdom, involving staff from a number of institutions.

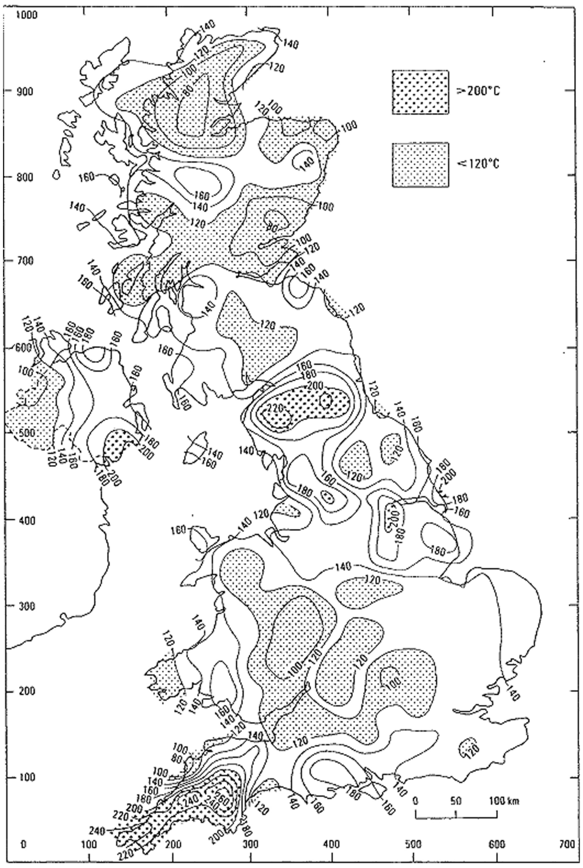

Figure 1. Predicted temperature in °C at 7kms in the UK (after Downing and Gray, 1986).

In Phase 1 (1977-80) of the project, boreholes were drilled to 300 m depth. These were used to demonstrate that is was possible to establish hydraulic connections between boreholes by injecting water at high pressures, thus increasing the permeability of the system by hydraulically developing the natural joints in the granite. Water was then circulated through these joints (Batchelor 1982).

Phase 2 (1980–1988) was considered to be more closely related to the conditions required for commercial exploitation of the technology and involved drilling two wells to a depth of 2.1 km. A reservoir was created by hydraulic stimulation but circulation of the system showed that although the stimulated reservoir, as identified by the distribution of the induced microseismicity, occupied a large reservoir rock volume, there was a poor connection between the injection and production wells.

A subsequent borehole was then drilled to a depth of 2.6 km at which the rock temperature was 100°C. This produced a smaller reservoir, with lower impedance and lower water losses (Parker 1989). The new reservoir was characterised by carrying out a continuous circulation at different flow rates, and measuring the hydraulic and thermal performance. The results showed that the reservoir was smaller than that required for commercial applications, and that at least 15% of the fluid was passing over a small surface area of rock, resulting in premature cooling of the production water (Camborne School of Mines 1989).

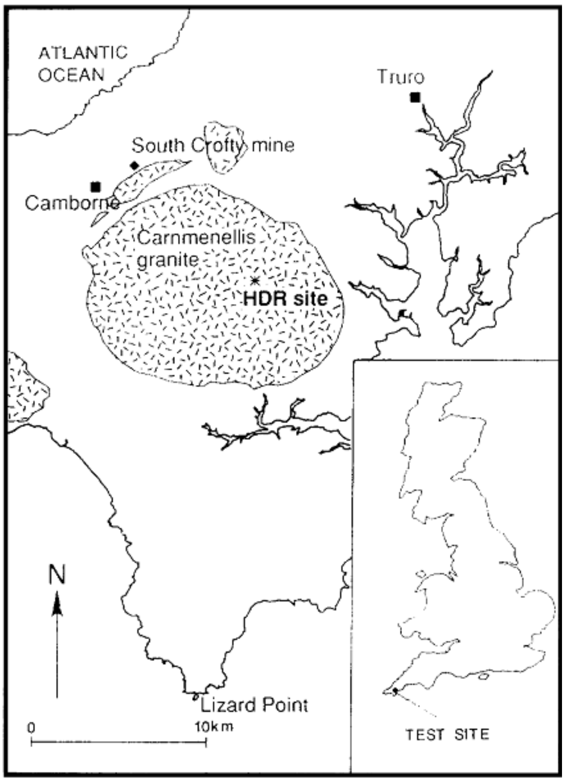

Figure 2: Location of the UK deep geothermal research project (after Richards, 1983).

Phase 3 began in 1988, with a conceptual design of a 6 km deep prototype of a commercial system for generating electricity in Cornwall. At this depth, rock temperatures over 200°C were expected. In addition to the conceptual design study, further research and development was also carried out, aimed at manipulating the Rosemanowes reservoir to improve its performance (Camborne School of Mines 1991). An important consequence of this work was a proposal to create large deep geothermal reservoirs by connecting smaller cells in parallel (Green & Parker 1992).

The Department of Energy decided in 1991 that the next phase of work would concentrate less on research in Cornwall and would involve greater collaboration with a European programme at Soultz-sous-Forets in Alsace, involving France, Germany and the European Commission. The Department's conclusion was that there were still very substantial technical uncertainties concerning the practicability of deep geothermal in the UK, and it seemed unlikely to be economically competitive in the short to medium term.

3. DEEP GEOTHERMAL IN 2009

The UK deep geothermal research project effectively stopped in 1991. In parallel, the geothermal power industry fell into a trough during the 1990s, primarily in response to very low oil prices. Since 2005 however, the geothermal industry has been in revival. This is due to a combination of concerns about climate change, energy security and the need for renewable base power. Deep geothermal systems have also been revived, particularly since the launch of the MIT report on the future of geothermal power in 2006 (MIT 2006). Deep geothermal exploration projects have started in earnest, primarily in Australia where the government has created a robust geothermal licence structure and match funding for deep geothermal projects. This pro-active approach has led to the establishment of a large number of deep geothermal companies (>30 in 2009), one of which has already declared 'proof of concept' at depths of 5km (Geodynamics, 2009). The US is about to follow suit following the announcement in February 2009 of a 10 fold increase in funding for geothermal to $400 million US. A large portion of this funding will be for deep geothermal projects.

In the UK it is now 18 years since deep geothermal exploration finished (with the notable exception of a 1.8km borehole in Southampton for heat supply). There is no geothermal licensing structure in place in the UK and, as this will require primary legislation, there will not be for at least two years. This has made development of projects in the UK more complex. However, despite this, it was decided in 2008 to revisit the data from the original UK experiment and select a new site with the ultimate aim of installing a power plant.

4. PROPOSED NEW UK PROJECT

Geothermal Engineering Ltd was formed specifically to develop the UK potential for deep geothermal power following a research programme undertaken by Ove Arup and Partners Ltd. Discussions were initiated with Dr Tony Batchelor (project director of the UK research project, now managing director of GeoScience) in 2008 on the most suitable process for developing a trial plant. The first step of the project was to conduct a new geological assessment, based on the data collected and experience gained from the UK research project.

The geological study was started in 2008 and is now complete. The study aimed to select the most appropriate site for the successful implementation of a 10MW (gross) electric power plant. A key aspect of the planned project was that it had to be economically viable and should not be categorised as a research project.

The study area comprised of the portion of west Cornwall from the St Agnes on the north coast to Helston in the south and from Truro in the east to Hayle in the west (Figure 3). This area incorporates and surrounds the Carnmenellis granite outcrop (approximate location shown by the grey circle in Figure 3). The Carnmenellis granite was the site of the UK deep geothermal research programme and, as a result, the subject of significant exploration activity. Of particular relevance to the study were the three deep wells drilled at the test site, extensive characterization of the granite fabric and natural fracture system, temperature and stress measurements, fluid and gas sampling and analysis and extensive hydraulic stimulation experience.

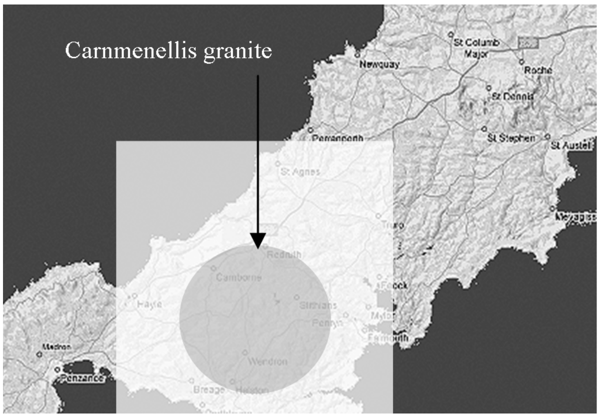

Figure 3: Proposed study area for the new project (square box).

The study area also includes a significant historical mining district that extends across the northeastern, northern and northwestern edge of the granite outcrop. Only one of the mines remains open today but extensive records exist of mining activity from the 19th and 20th centuries, penetrating both the granite and killas to depths of 1,000m. These records provide valuable insight into the nature of the rock fabric and natural fractures, temperatures, and the occurrence of hot water inflows.

5. GEOLOGY

As a result of the research projects undertaken in the 1970s it is now broadly agreed that some degree of natural permeability needs to be present for the successful development of a deep geothermal system. To assess and compare suitable targets at depth the study defined a number of geological 'domains' which were then evaluated using the following criteria:

- Fracture permeability
- Domain volume
- Temperature

The geology of the study area is highly complex and has been reported in detail in many technical papers (see Parker 1989 Volume 1 for a comprehensive review and reference list). The geology is briefly summarised here. The main phases of geological history are, in chronological sequence from oldest to youngest:

Upper Devonian: marine sedimentation dominated by fine-grained bedded lithologies (black siltstones and mudstones) but also with sandy horizons and occasional carbonates. Known locally as 'killas', it also contains intrusive and extrusive igneous rocks occurring mainly as sills or layer-parallel bodies (known as 'greenstones')

Mid-Late Carboniferous: Variscan continental collision and low grade metamorphism, causing complex deformation of the killas with ~NNW-directed thrust sheet emplacement, crustal thickening and uplift. Shortening part-accommodated by strike-slip faults oriented ~NNW-SSE (some may be reactivation of earlier Devonian structures)

Late Carboniferous to mid-Permian: post-collision regional extension with intrusion of granitic plutons and two phases of hydrothermal mineralisation. This is hosted in ESE-WNW striking mineral 'lodes' and in NW-SE to N-S striking 'cross-course' structures, many of which are reactivations of the earlier strike-slip faults

Mid-Permian and Triassic: continued post-Variscan extension and associated red bed sedimentation (including New Red Sandstone, preserved in Plymouth Basin)

Jurassic through Cretaceous (~143Ma): details uncertain due to absence of rocks of this age in SW England. Significant uplift of Cornubia and granite unroofing took place from mid-Jurassic to mid-Cretaceous, with subsequent Chalk deposition due to thermal subsidence

Tertiary: deposition of marine deposits at least locally (remnants remain at St Erth and at St Agnes, probably Pliocene in age). Also significant regional uplift and erosion including removal of the Chalk (remnants of a late Miocene/ Pliocene marine platform are found at ~134mOD around Camborne for example). Possible reactivation of the cross-course fault family in association with Alpine collision

The key potential lithologies identified for the study are summarised below:

D1 Background granite

Granite with normal or 'background' fracture intensity, typical blocky fracture network.

D2 Faulted granite

Granite with high fracture intensity due to presence of faults and / or fracture corridors, plus alteration effects .

D3 Background killas

Devonian formations with normal or 'background' fracture intensity.

D4 Faulted killas

Devonian formations with high fracture intensity due to presence of faults and / or fracture corridors, plus alteration effects.

D5 Flank contacts between granite and killas

Steep to moderate dipping contacts due to stoping and / or faulting, with associated intrusives in the killas and alteration effects.

D6 Roof contacts between granite and killas

Flat-lying contacts due to stoping, with associated intrusive complexes in the killas and alteration effects.

D7 Major structural Intersections

Intersections between major faults, fault zones or folds.

In light of the experience of the UK research project arguments for and against each of the domains were developed based on the assumption that evidence of naturally enhanced permeability is the most desirable attribute of a lithology. The arguments for and above the following formations are summarised below:

D1 Granite

For: Systematic orthogonal joint sets, master joints, fracture corridors.

Against: Variable and reducing fracture frequency and aperture with depth, limited connectivity.

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D2 Faulted granite

For: High fracture frequency, vuggy fault cores, good connectivity

Against: Narrow damage zones, may be kaolinised with porosity occlusion

D3 Killas

For: No merit

Against: Non-systematic joint sets, many sealed, low fracture dimension and frequency

D4 Faulted killas

For High fracture frequency, vuggy fault cores, wide damage zones, good connectivity, limited alteration effects

Against: Possible argillic alteration on fracture surfaces

D5 Flank contacts

For: Potential for high fracture density in brittle formations and metamorphic aureole

Against: Many sealed fractures, localisation of faulting at contact very unpredictable

D6 Roof contacts

For: Potential for high fracture frequency in brittle formations and metamorphic aureole

Against: Many sealed fractures, unlikely to be faulted contact

D7 Structural intersections

For: High fracture frequency, high flow potential

Against: Potentially sealed fractures if structures are 'fossilized'

The nature of the fracturing in both the Killas formation (above) and the granite formation (below) can be most clearly seen in Figure 4. The granite displays a block like fracture network where as the Killas is more intensely fractured. The Killas also displays more intense Iron staining implying more host rock permeability.

The major controlling factor for the site is that significant faulting is required in order to elevate fracture permeability above background levels, be it granite or killas. Moreover, higher fracture density and the potential for enhanced permeability is likely to exist at structural intersections and in zones of major structural intersection. A further, but more contentious conclusion is that faulted killas may be more suited as deep geothermal host. This is suggested mainly because fault damage zones tend to be wider than those in granite (for the same displacement fault), as can be seen in Figure 4, where metric scale fractures and fracture corridors change character when crossing from one formation to the other. A second factor is that fractures in the killas may be less prone to alteration affects.

Significant uncertainty remains about whether these dominantly near-surface observations can be extrapolated to 4,000m depth. Borehole evidence indicates the possibility of this to at least 2,000m in Cornwall, and to greater depths in other locations (eg at the San Andreas Fault California, and the Kola Peninsula deep borehole). However, even if secondary alteration is present and acting to occlude fracture porosity, this may be countered by active stress dilation of fractures, at least for those of susceptible orientation. In the absence of these factors the hydraulic properties of fractures in granite and killas at 4,000m depth may be similar.

Figure 4: Fault structure showing the difference between granite (below) and killas (above).

6. GRANITE GEOMETRY

Gravity modelling of the Carnmenellis granite was carried out in connection with the deep geothermal research programme (ETSU,1989), and more recently by Taylor (2007) on the basis of new developments in understanding pluton intrusion mechanisms. These two pieces of work propose different interpretations of the shape of the granite which impact significantly on the geological prognoses at 4,000m.

The ETSU modelling predicted continuity of the granite to a depth well beyond 5,000m, with the granite / killas contact generally dipping outwards and a typical trapezoidal or diapiric shape for the pluton. The base of the granite was constrained in this work to honour a mid-crustal gently south dipping reflector identified at ~10km depth in seismic profiles (the R2 reflector of Brooks et al 1984), which may represent a north directed Variscan thrust. The top of the granite was then fitted to honour the gravity data. The model predicts a steep granite / killas contact on the south and east sides of the pluton and shallow table-like top granite geometry to the north and west of the outcrop.

Taylor (2007) took an opposite approach, studying the short wavelength (near-surface) gravity profile and constraining the model using the surface outcrop and near-surface shape of the granite, and predicting the base of the granite body instead. He also drew heavily on recent modelling studies of magma ascent and intrusion, and pluton geometries observed at outcrop (e.g. Grocott et al 2009), and seismic interpretation of the Lake District batholith (Evans et al 1994). These studies are exemplified by Clemens (1998), Cruden (1998) and Petford et al (2000) all of whom favour flat lying semi-tabular geometries for mid- to upper-crustal intrusions, ranging from laccolith to lopolith in form and rooted on a central narrow 'feeder' where the magma ascended (Figure 5). The intrusions tend to have vertical or inward dipping contacts and to be floored at relatively shallow depths (Clemens 1998). In addition, measurements of length-to-thickness ratios for 156 granite plutons around the world (McCaffrey and Petford 1997) revealed a tendency for these ratios to be scale-invariant, reflected by a power-law relationship:

$$t = 0.12\ L^{0.88}$$

where t = thickness and L = largest horizontal dimension

This relationship predicts that a 50km diameter pluton will have a thickness of 3.75km, and a 30km diameter pluton will be 2.39km thick. The edges of the Carnmenellis granite are hard to define but the diameter is probably around 50km (± 10km), see Brooks et al (1984). As a result of these considerations, the gravity modelling by Taylor (2007) predicts a mushroom-shaped geometry for the granite (Figure 6), with an inward dipping contact from ~2,000m depth and a base at ~ 4,000 to 5,000m at the southern edge. The depth to base predicted is consistent with the power law relationship given above.

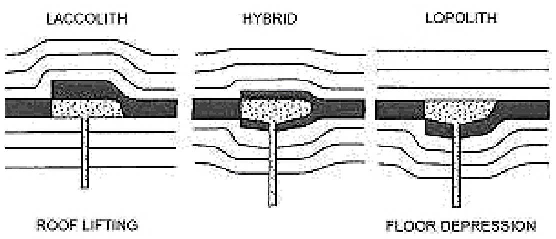

Figure 5: Model of tabular granite emplacement (after Cruden 1998)

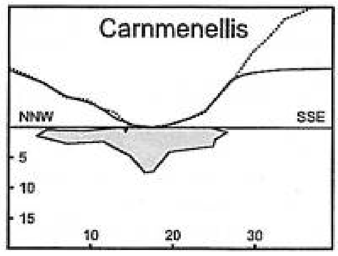

Figure 6: Gravity model for the Carnmenellis pluton. Scale in kms (after Taylor 2001).

However, in order to account for the observed heat flow of the Carnmenellis granite it is necessary to invoke deeper layers of granite in approximate sill-like geometries, resulting in a 'cedar-tree' geometry extending below 5,000m. A deeper sheet (or sheets) of low density granite is also required by the Taylor (2007) gravity modelling itself to explain the longer wavelength variations in the gravity field (due to a deeper source), and this helps to reconcile the differences with the ETSU (1989) model. The exact geometry and scale of the granitic sill / killas host rock bodies which 'interweave' to form the contact zone are unknown, however an analogue is provided by seismic reflection mapping of the western margin of the Lake District batholith (Evans et al 1994). This reveals complex interfingering of granitic sheets with the country rock at scales of 100 to 1000m.

From the discussion above it is apparent that the Carnmenellis gravity modelling is ambiguous and depends on assumptions that cannot be tested. The recent interpretation by Taylor (2007) cannot be ruled out because it is based on outcrop observations, seismic mapping, and analysis of magma intrusion processes that post-date the work carried out in the 1980s.

7. STRESS REGIME

Many publications have shown that in-situ stress influences fracture aperture and hence permeability (see Tamagawa and Pollard 2008 for a recent review). The present-day stress field in Cornwall is relatively well understood from downhole measurements made in the Carnmenellis granite (Batchelor and Pine 1986, Parker 1989). The magnitudes and orientations of the principal stress axes were measured from near-surface to 2,500m revealing significant stress anisotropy. The implied strike-slip stress regime is consistent with focal plane solutions from microseismic monitoring carried out during the research project.

The microseismic events which were produced during the injection formed a linear 'cloud' close to the orientation of a major joint set identified in the granite (Figure 7). It was concluded that injection was promoting minor slip on these fractures because they are in a state of critical shear in the current stress field. Similar work carried out in the Troon boreholes (Heath 1985) also concluded that fractures oriented approximately NNW-SSE were preferential flow paths, but also noted that flow was taking place in many fractures with strikes orthogonal to σ Hmax during injection in the wells, which indicated predominantly strike-slip motion on fractures oriented at ~25° to σHmax.

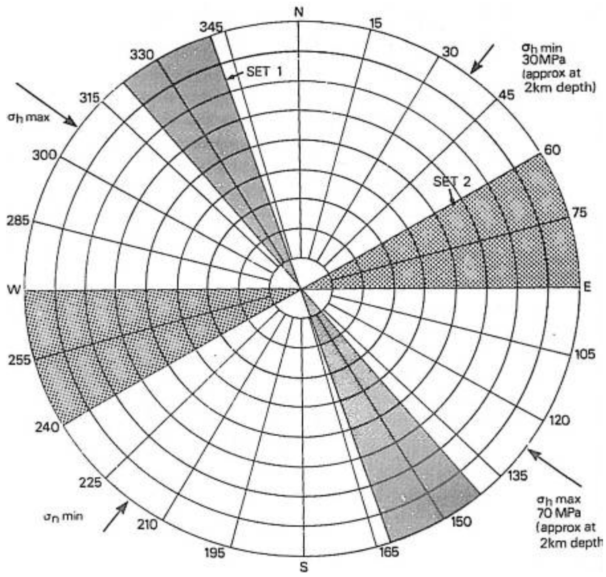

Figure 7: Strike directions of major joint sets and horizontal in situ stresses in SW England (Batchelor and Pine 1986).

These conclusions are in general agreement with the observations of water ingress in mines, which indicate that the NW-SE to N-S striking cross-courses are the main sites of persistent flows, often at intersections with the WSW-ENE striking lode structures (BGS 1989). The cross-course flows were reportedly persistent for many years, and produced water at 40 to 60°C.

Based on the assessment above, it was concluded that fault zones with enhanced and connected fracture permeability at 4,000 to 5,000m depth are the most suitable geological domain for hosting a deep geothermal power plant and this formed the basis for the site selection.

8. TEMPERATURES

The whole study area is underlain by a high heat production granite, the surface expression of which is known as the Carnmenellis Granite. Heat is generated within the granite by the decay of Uranium, Thorium and Potassium, resulting in elevated heat flow compared to average rocks in the UK. It was assumed at the outset of the study that the whole study area would have higher than average temperature gradients and that the geological criteria were more significant in choosing the target site.

9. UNCERTAINTIES

During the course of the study it became apparent that there is a moderate to high degree of uncertainty surrounding the prognosis of geological formations and structures at 4,000 to 5,000m depth. This is true despite the wealth of surface and near-surface data (at least in parts of the study area), and follows from the absence of well control and the coarse resolution and ambiguity of geophysical remote sensing methods. Certainty will only be achieved when an exploration borehole is drilled.

10. SUMMARY

Extensive research has been undertaken in the UK to identify deep geothermal resources. Further to this a large scale research project was undertaken (1976-90) to understand the issues associated with establishing hydraulic connections at significant depths. The renewed global interest in deep geothermal technology has lead to the establishment of Geothermal Engineering Ltd to develop a trial geothermal power plant in the UK. A geological and logistical feasibility study was started in 2008 and has now been completed. Based on the existing data and experience gained during the research project a site has been chosen that it is hoped will display enhanced natural permeability at depths of approximately 5kms. The drilling of an exploration borehole on the site is expected to start in 2010. Despite the large amount of data on the chosen area there are still some uncertainties as to the geology that will be encountered at depths of between 4 and 5kms. This will only be resolved once the exploration borehole is complete.

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